The Rate of Transmission of the Guatemala Earthquake, April 19, 1902.

By R. D. Oldham.

(Communicated by Professor John Milne, F.R.S. Received February10,—Read March 9, 1905.)

In 1900 I showed,* by a critical examination of the records of earthquakes, obtained at a distance from their origin, that three distinct forms of wave motion could be recognized, to which I applied the terms first, second and third phase, and that these travelled along different paths and at different speeds. It was suggested that the first and second phases represented the outcrop of condensational and distortional mass waves, which had travelled through the earth, and that the third phase was due to waves, partly elastic and partly gravitational, which had travelled along or near the surface. These explanations have not been universally accepted, and alternative suggestions have been made, but the distinction of the three phases has been generally recognized, the nomenclature adopted, and the first two phases accepted as mass waves travelling through the earth. This last conclusion has been borne out by the time-curves published by Professor Milne, who, using data whose greater abundance compensated for a lesser degree of precision, deduced a set of time-curves essentially identical with mine, in that they showed a curvature in the first two phases which is only compatible with the supposition that they belong to mass waves.†

In Japan these conclusions have never been formally traversed, but in the more recent publications of that country we find that no less than eight phases are recognized, and designated by the symbols P_1, P_2 . . . P_8; of these P_1 and P_2 correspond to the first and second phases of the last paragraph, while the remainder constitute the third phase. The nature of these third phase waves is still a very open question, and it is doubtful whether there is any real difference in the character of the wave motion of P_3, P_4, P_5, etc., or whether we are not dealing with waves of essentially similar nature, whose rate of propagation is a function of their period; in any case it is acknowledged that these waves are propagated along or close below the surface of the earth. The same conclusion is, however, also adopted for the first two phases, and the

* 'Phil. Trans.,' A, vol. 194, pp. 135—174 (1900).

† 'British Assoc. Rep.,' 1902, p. 66.

rectilinear character of their time curves apparently established by Dr. Imamura, on the basis of a large number of observations.*

As this point is of some importance, it seems desirable to devote a few words to the consideration of the nature of the evidence on which the curves are drawn. I find that of 85 earthquakes dealt with, 31 originated in or near Japan, and no record except that at Tokio is given; of the remaining 54, the time and place of origin was known by direct observation in only five cases, in one of which the time adopted is erroneous; in three more the place but not the time of origin was known, in 25 the place of origin is only approximately known, and in 21 it is inferred from observations at a distance. In all these 49 earthquakes the time of origin was calculated from observations at a distance, by the use of a formula based on the assumption of a uniform apparent rate of propagation; in these circumstances it is not surprising that the resulting intervals show a close approximation to a rectilinear time-curve.

Of the five earthquakes whose time and place of origin were supposed to be known with accuracy, great importance is attached to that of April 19, 1902, originating in Guatemala, and Dr. Imamura has made a detailed study† of it which he regards as supporting his views, but he was misled as to the time of origin, and, moreover, obtained his times, other than those of commencements, from figures published in the *British Association Earthquake Circular*, No. 6. As these figures are printed from blocks, which were drawn from photographic copies of the original traces, the times obtained from them naturally differ from those obtained by direct measurement on the original trace, or on a photographic copy of it.

In these circumstances it has seemed desirable to re-examine the records of this earthquake, and to determine, so far as possible, the true time of arrival of, at least, the first and second phases of wave motion at all stations where they were recorded. By the generosity of Professor Milne, who placed at my disposal not only the photographic copies of the records of the Milne pendulum stations, but also the reports from other observatories and the correspondence relating to the time of origin, it has been possible to compile a record of this earthquake more complete than has yet been published in the case of any other.

Sec. 2. *Definitions.*—Before proceeding to the consideration of the records it is desirable to define the exact sense in which the words first, second, and third phase are used and interpreted from the records.

* 'Publications, Earthq. Investigation Comm. Foreign Languages,' No. 16 (1904).

† 'Publications, Earthq. Investigation Comm.,' No. 16, p. 112

The *first phase* is normally the commencement of the record: as exceptions we may find that—

(1) The instrument is affected by tremors before the normal commencement, whether these belong to the same disturbance or an independent one.

(2) The instrument, failing to respond to the first impulse of the shock, may respond to a later impulse in those cases where the disturbance is caused by more than one original impulse.

(3) The instrument may fail to respond till the arrival of the wave motion due to the second or third phases.

Each of these causes of error is easily detected when a number of records are compared with each other.

The disturbance due to the first phase is seldom of more than small amplitude in the case of instruments recording the horizontal components of the motion; in the vertical component of the Vicentini instrument the disturbance due to this phase is greater than that of either of the other two.

The *second phase* is marked by an abrupt and considerable increase in the amplitude of the disturbance. In the case of pendula of five seconds or less in period the maximum amplitude is almost invariably found in this phase; the vertical component, on the other hand, rarely shows even the slightest disturbance. This distinction in the character of the records would, in itself, be sufficient to show that the first and second phase waves were very different in character. On instruments giving an open diagram, the period of the waves in this phase is always longer than in the first phase.

The *third phase* sets in with long period waves, followed by quicker, but always longer period than met with in the first two phases. In larger disturbances, at least, this phase is always accompanied by a certain amount of surface tilting, though this is apparently much less than was supposed a few years ago. In Europe it is usual to give the time of maximum amplitude of disturbance, and the practice seems useful, although the importance attached to these maxima has been questioned, and they have been regarded as diagrammatic, for which I should prefer to write instrumental.* The researches of Prince Galitzin† and Professor Rudzki‡ have shown that a perfectly frictionless horizontal pendulum would not record truly a regular periodic movement of its support, as it would acquire a pendular swing of its own, and the record would be a combination of this with that due to the movement of the ground. Seeing that the desire of constructors of seismographs has always

* A. Imamura, 'Rep. Tokyo Physico-Mathematical Society,' No. 20, p. 1 (1904).

† 'Comptes Rendus de la Comm. Sismique Permanente, St. Petersburg,' vol. 1, pp. 101—183 (1902).

‡ 'Beiträge z. Geophysik,' vol. 6, pp. 138—155 (1904).

been the most complete elimination of friction that they can attain, it is not improbable that these conclusions apply in a modified manner to the records of seismographs; in addition it must be remembered that there is probably no defined maximum of the disturbance recorded, and in view of these two considerations it is possible that too much importance has sometimes been attached to the exact time of maximum amplitude of the record. On the other hand, it is impossible to see the well-defined maxima, having often three or four times the amplitude of any other part of the record, which are not infrequent, without regarding them as recording a reality rather than a mere instrumental accident. For this reason I have followed custom in recording the time of maximum displacement in the third phase.

Sec. 3. *Place and time of origin.*—The place of origin can be determined with sufficient accuracy from the maps published by Messrs. Rockstroh* and G. Eisen.† From the former an origin may be deduced as in about N. lat. 15°, W. long. 92°; according to the latter in N. lat. 14°, W. long. 91° 30′. For the purpose of calculation of distances, the origin has been assumed as N. lat. 14° 30′, W. long. 91° 15′.

The time was given by Mr. Rockstroh, on the strength of a single observation, as 8.25 P.M. local time; this was the time used by Dr. Imamura, but fortunately it can be checked, for it so happened that a block of buildings was set on fire by the overturning of a lamp, and burnt down at this time. The buildings were insured against fire, but not, as stipulated in the policy, against fire caused by earthquake, and it became a matter of importance to decide whether the lamp was upset by the earthquake, as claimed by the insurance company, or before the earthquake, as claimed by the owners; as a consequence of this dispute, the time of occurrence of the earthquake became the subject of careful inquiry, and the time finally accepted was 8.20 P.M. local time. The time used throughout the Republic of Guatemala is 6 h. 2 m. 3 s. slow of Greenwich mean time,‡ so the time of origin of the earthquake may be taken as 2 h. 22 m. Greenwich mean time.

Sec. 4. *The observations.*—As there does not seem to be any necessity for reprinting every published record of the earthquake, I shall merely give a

* 'Nature,' June 12, 1902.

† 'Bull. Amer. Geog. Soc.,' vol. 35, p. 325 (1903).

‡ J. Milne, "Civil Time," 'Geogr. Journ.,' February, 1899. For the particulars in this paragraph I am indebted to Professor Milne. The case may be quoted as a practical application of the new seismology; for the insurance company, when involved in the dispute, wrote to Shide, inquiring whether any information as to the true time of occurrence of the earthquake could be given, and the time deduced from the records of the British Association organisation proved to be within some seconds of the time finally adopted after local inquiry.

tabular statement of times and a note in explanation of the sources of information, and of any differences which may be found between the times given and those originally published.

Tabular Statement of the Recorded Time of Arrival of each of the Three Principal Phases of Wave Motion. Guatemala Earthquake of April 19, 1902. Times in Minutes after 2 hours Greenwich Mean Time.

Distance.	Station.	I phase.	II phase.	III phase.
		min.	min.	min.
27°·8	Baltimore	30·1	35·6	40·3
30·8	Toronto	30·5	35·5	38·0
43·0	Victoria, B.C.	31·3	37·2	50·7
52·7	Cordoba, Arg.	32·1	39·1	45·3
76·2	Paisley	(22·0)	(43·0)	73·0
77·0	Edinburgh	36·0	45·5	74·5
77·4	Bidston	35·0	—	75·1
77·6	San Fernando	34·8	(43·3)	61·8
78·8	Shide	35·4	46·8	79·2
78·8	„	35·5	46·9	78·7
78·8	„	35·5	46·9	73·0
79·3	Kew	36·2	45·8	70·1
82·3	Uccle	36·0	46·4	—
84·9	Hamburg	36·3	46·6	80·4
85·0	Strassburg	36·2	—	—
88·6	Padua	36·6	47·0	69·6
88·6	„	36·6	(47·1)	69·7
88·6	„	36·6	47·3	69·7
88·6	„	36·6	47·3	73·4
88·7	Florence	37·0	47·4	68·0
88·7	„	36·7	47·2	70·0
88·7	„	36·0	46·1	68·0
90·2	Trieste	36·8	(48·9)	—
90·2	Rome	37·6	(50·3)	73·0
90·2	„	37·6	—	—
90·4	Quarto Castello	37·0	47·5	68·5
90·4	„	36·6	47·0	69·0
90·4	Rocca di Papa	36·7	47·0	72·5
90·4	„	36·8	48·3	—
90·4	„	36·7	47·1	76·8
90·4	„	36·8	47·1	71·2
90·4	„	37·6	47·0	72·5
90·4	„	37·6	47·0	—
91·4	Juriew	36·6	46·2	—
91·4	„	36·6	—	73·0
91·4	„	37·3	47·4	—
91·7	Ischia	37·0	47·6	72·0
92·4	Pawlovsk	—	47·2	73·3
93·6	Catania	36·7	—	71·5
93·6	„	(41·0)	—	74·5

Tabular Statement—*continued.*

Distance.	Station.	I phase.	II phase.	III phase.
		min.	min.	min.
100°·3	Nicolaiew	37·0	(52·0)	70·0
102·5	Wellington, N.Z.	38·0	47·0	79·0
104·5	Christchurch, N.Z.	37·2	48·0	79·2
110·4	Tokio	(41·6)	(49·6)	—
110·4	„	(38·8)	(53·0)	—
110·7	Tiflis	38·2	(56·6)	86·1
110·7	„	38·2	(56·5)	86·0
110·7	„	38·3	(56·4)	85·2
111·9	Irkutsk	(43·7)	51·5	85·9
111·9	„	(41·7)	(58·8)	96·4
111·9	„	(43·2)	(58·5)	99·9
113·9	Capetown	38·4	51·6	86·0
121·3	Tashkent	39·9	49·2	—
121·3	„	40·5	50·1	—
142·9	Calcutta	44·0	—	(73·5)
144·1	Bombay	43·3	64·5	107·0
144·1	„	43·8	66·8	108·4
144·1	„	43·4	—	109·1
149·8	Perth, W.A.	43·8	62·0	—
152·9	Kodaikanal	(39·0)	(59·4)	107·2
160·4	Batavia	43·7	68·0	109·0

Note Explanatory of the Statement.—Each line refers to the record of a distinct instrument, or at least to an independent pendulum, except in the case where two consecutive records at the same station are bracketed together; in these cases the times refer to the two components into which the movement of a single mass is resolved. Figures enclosed in brackets indicate either that there is an uncertainty in the interpretation, or that a comparison of the times with those at other stations shows that they cannot refer to the phase of the record to which at first sight they would naturally be referred.

It will be observed that the list of records contains several groups of about equal distance from the origin, which are indicated by the long brackets on the right-hand side of each row of figures, and in dealing with the results it will be best to take the mean of each group, thereby eliminating, to a large extent, the minor errors which may affect individual observations. Treated in this way, we get the following series of group-averages of time of arrival, to which I have added the corresponding mean rate of transmission from the origin, expressed in degrees of arc per minute of time. This way of

expressing the rate of transmission seems preferable to the more usual one of kilometres per second, as the latter always requires qualification, being meaningless unless accompanied by a statement of the line along which the distance is measured.

Group-average Times of Commencement of First and Second Phases, and of Maximum of Third Phase; also Mean Apparent Rate of Propagation in Degrees per Minute.

Distance.	First phase.			Second phase.			Third phase, max.		
	Obs.	Time.	Rate.	Obs.	Time.	Rate.	Obs.	Time.	Rate.
deg.	No.	min.	deg.÷min.	No.	min.	deg.÷min.	No.	min.	deg.÷min.
0·0	—	22·0	—	—	22·0	—	—	22·0	—
29·3	2	30·3	3·53	2	35·5	2·17	2	39·1	1·71
78·0	7	35·5	5·78	5	46·4	3·20	6	75·1	1·47
90·8	20	36·8	6·14	14	47·1	3·62	19	71·4	1·84
102·4	3	37·4	6·65	2	47·5	4·02	2	79·1	1·79
112·2	4	38·3	6·88	2	51·5	3·80	7	89·4	1·66
145·6	5	43·7	6·71	2	63·3	3·53	3	108·2	1·69
160·4	1	43·7	7·39	1	68·0	3·55	1	109·0	1·84

This statement shows that in the *first phase* the apparent rate of transmission increases continuously with the distance, if we except the decrease at about 145°, which may be due to the commencements being late, or to those in the group before it being early. In any case the figures show that the time-curve is not rectilinear, though the recorded times show an approximation to a uniform rate of about 9·7 degrees per minute between the limits of 30° and 90° from the origin. This part of the time-curves, as drawn by Professor Milne and by myself, shows an approximation to a straight line and the curvature only becomes conspicuous when they are extended beyond these limits. In the case of the Guatemala earthquakes, we have no observations at less than 28° from the origin, but the more distant records—if we except the aberrant one from Kodaikanal—seem to show that the emergence of this phase of wave motion was practically simultaneous from 140° to 160°, a phenomenon which might be explained on the hypothesis of mass waves, but not on that of waves propagated parallel to the surface. It is not, however, advisable to attach much importance to the more distant records till they have been confirmed by others; up to 90° from the origin we have a sufficiently complete series of mutually corroborative records.

The *second phase* shows the same feature as the first, of an increase of apparent rate of propagation with distance, but this only continues to about

100° from the origin; beyond that there seems to be a decrease. This result is unexpected, but must not be rejected merely on that account, yet it is worth noting that the second phase is much less well marked in these distant records than in the nearer ones. On the Milne pendula the absolute maximum of displacement is ascribed to this phase, but on the horizontal pendula with mechanical registration at Bombay, this phase is hardly marked on one and not at all on the other.

Of the *third phase* little need be said; the apparent rate of propagation is, on the whole, uniform, the irregularities being sufficiently accounted for by the causes referred to in Sec. 2.

The sources from which the data were taken are: for the Milne pendulum stations, the circulars of the Seismological Committee of the British Association; for the Italian records the 'Bolletino della Società Sismologicà Italiana'; for the Russian records the 'Bulletin de la Commission Centrale Sismique Permanente'; and for other places the periodical reports of the observatories. In addition to these the examination of the photographic reproductions of the Milne pendulum records has enabled me to add particulars regarding the time of the second phase which are not given in the British Association circulars. A few Italian stations where only the time of commencement was recorded have been omitted. The notes following refer only to those cases where there has been any difficulty of interpretation, where this has been simple and straightforward it is not necessary to reprint the original record.

Paisley. The whole record is marked by air tremors, and only the time of maximum is determinable. The second phase seems to have commenced at 2 h. 43 m. or thereabouts.

San Fernando.—The second phase cannot be clearly distinguished from the effects of the successive impulses, recognizable on this as on other traces.

Tokyo.—From this place we have two records. One, by Professor Omori, in the British Association circular, which gives the commencement at 2 h. 41·6 m., L.W. commence at 2 h. 49·6 m., maximum 2 h. 50·9 m. The other, published by Dr. Imamura in his account of the Milne pendulum seismograms, obtained at Hongo, Tokyo,* gives the times as P_1, 2 h. 38·8 m., P_2, 2 h. 53·0 m., with an instrumental maximum shortly after. The reproduction of the seismogram does not help matters, as it differs so much in type from those at other stations: the time, 2 h. 38·8 m., is about what would be expected for the commencement from a comparison with other records, and 2 h. 49·6 m

* 'Publications, Earthq. Investigation Comm.,' No. 16, 1904, p. 89.

would not be far from the time for the second phase, but in view of the doubt attaching to the interpretation of the records from this station, I have thought it best to exclude them all.

Irkutsk.—All the instruments at this station appear to have commenced with the second impulse, which can be found on most records at about 4 m. after the first. On the Milne pendulum the recorded commencement is preceded by a small disturbance of the trace, whose beginning is gradual and cannot be fixed, though it is visible for some minutes. The second phase commencement is at 2 h. 51·5 m. on the Milne pendulum trace, the other times on this column are those recorded for reinforcements on the traces of two horizontal pendula.

Tashkent.—The first tremors are recorded at 2 h. 34·5 m. and 2 h. 34·8 m., the times in the table are those of the first reinforcements, which evidently correspond to the first phase in the records of other stations.

Bombay.—The recorded maximum is at 3 h. 8 m. or 3·5 m. after the first marked increase in amplitude, which is taken to represent the second phase. Slow oscillations, marking the third phase, set in at 3 h. 27 m., and are slowest at 3 h. 39 m., when the trace is quite open; they become quicker and attain a maximum amplitude, almost as great as that of 3 h. 8 m., at 3 h. 47 m.

Besides the Milne pendulum there are two heavy horizontal pendula. I am indebted to Dr. N. A. F. Moos for the tracings of their records, from which the following particulars have been taken.

Hor. Pend., E.W.—Commencement 2 h. 43·8 m.; at 3 h. 6·8 m. there is a sudden displacement and another, larger, at 3 h. 11·7 m., these consist in each case of a single oscillation and seem to represent the second phase, maximum of third phase at 3 h. 48·4 m.

Hor. Pend., N.S.—Commencement 2 h. 43·4 m.; the second phase is not recognisable; maximum of third phase at 3 h. 49·1 m.

Kodaikanal.—The record as given in the British Association Circular No. 6 is: commencement 2 h. 39·0 m., maxima 3 h. 0·4 m., 3 h. 6·7 m., 3 h. 10·8 m., 3 h 47·2 m., 3 h. 52·3 m.; amplitudes, 0·8 mm., 0·5 mm., 0·5 mm., 0·4 mm., 0·5 mm. The trace itself shows a very small amplitude throughout, and the five maxima form a series of small bulges arranged in two groups of three each, the sixth being at 3 h. 56·5 m. Here the maximum at 3 h. 0·4 m. seems to belong to the second phase, which would then begin about 1 m. earlier.

The most remarkable feature about this record is the time; both commencement and second phase are some four or five minutes earlier than would be expected from the records at other observatories of about the same epicentral

distance. The easiest explanation would be to assume an error in the time, but this supposition is inadmissible in an astronomical observatory, one of whose functions is the giving of a daily time signal. The discrepancy must remain inexplicable, and in view of it, and of the doubt in the interpretation, the record has been excluded from consideration.

Batavia.—The diagram is rather indefinite; there is an increase at about 4 m. after the commencement, probably marking the second impulse, but the first considerable increase is about 25 minutes after the commencement. This probably represents the second phase, of which the beginning is indistinct, and to which the maximum at 3 h. 12·4 m. belongs; the maximum of the third phase is at about 3 h. 49 m.

A Determination of the Amounts of Neon and Helium in Atmospheric Air.

By Sir William Ramsay, K.C.B., F.R.S.

(Received March 11,—Read March 16, 1905.)

Some time ago I communicated to the Society* the results of an attempt to estimate the amounts of krypton and of xenon in air. The quantities were necessarily minimum estimates, for there is no doubt that both krypton and xenon must evaporate when air evaporates, even if that take place at a very low temperature. Dr. Travers and I guessed at the amounts of neon and helium, and supposed that the amount of helium was one or two parts per million, and that of neon one or two parts per 100,000. This guess is not very far from the truth, as the following account of recent experiments will show.

The ingenious method discovered by Sir James Dewar of using cooled cocoanut charcoal as an absorbent for gases has made it easy to carry out the estimation. The process consists in cooling 100 grammes of such charcoal to $-100°$, approximately, in a bulb from which all air has been removed by a pump. Such charcoal will absorb about three litres of air; at that temperature neither neon nor helium are absorbed in appreciable quantity, as special experiments showed. Hence on placing the cooled bulb containing the charcoal in communication with a Töpler pump, the uncondensed gases enter the barrel of the pump. On closing the connecting stop-cock, a further quantity

* 'Roy. Soc. Proc.,' vol. 71, p. 421.